Supersaturation in X-ray emission of clusters stars

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Abstract. A population of cool dwarfs with extreme rotational velocities (vsin $i \gtrsim 100$ km/sec) is present in young open clusters. ROSAT observations have shown that these very fast rotators exhibit a level of X-ray activity a factor of 3–5 below the saturated level which is usually observed (both in X-rays and other magnetic activity indicators) for 'normally' fast rotators. This phenomenon has been denominated *"Supersaturation"*.

W UMa contact binaries seem to be supersaturated as well, while the scatter in the rotation-activity relation for RS CVn and BY Dra binaries does not allow us to clearly discern whether they exhibit supersaturation or not. Supersaturation is not seen in Hα for α Per supersaturated stars.

Two alternative lines of interpretation are discussed.

1. Introduction

Saturation of magnetic activity is, from an observational point of view, a well known phenomenon, though it represents an open problem within the framework of dynamo theory.

Einstein, IUE, and, later, HST and ROSAT observations of stars in open clusters and in the field have shown that the ratio of chromospheric and transition region line fluxes over bolometric flux ($f_{\rm line}/f_{\rm bol}$), as well as the X-ray to bolometric luminosity ratio (L_X/L_{bol}), generally increases with increasing rotation, until a saturation plateau is reached (e.g., Vilhu and Rucinsky, 1983; Vilhu 1984; Simon and Fekel 1987; Simon 1990; Stauffer et al. 1994; Randich et al. 1996; Ayres et al. 1996; Patten and Simon 1996; Stauffer et al. 1997ab). In other words, saturation indicates that, outside of flaring, the radiation emitted from plasma at temperatures of $\sim 10^4$, 10^5, and 10^6-10^7 K, respectively, cannot exceed a given fraction of the total stellar flux, even in most active stars. For X-rays such a fraction is 1/1000, or $L_X/L_{bol} = 10^{-3}$.

Saturation lacks an agreed upon interpretation; it is not clear whether it reflects the saturation of dynamo itself or it is rather due to the total filling of the star's surface with active regions, as originally suggested by Vilhu (1984). We mention in passing, that saturation in angular momentum loss needs to be introduced in the models of angular momentum evolution in order to explain the

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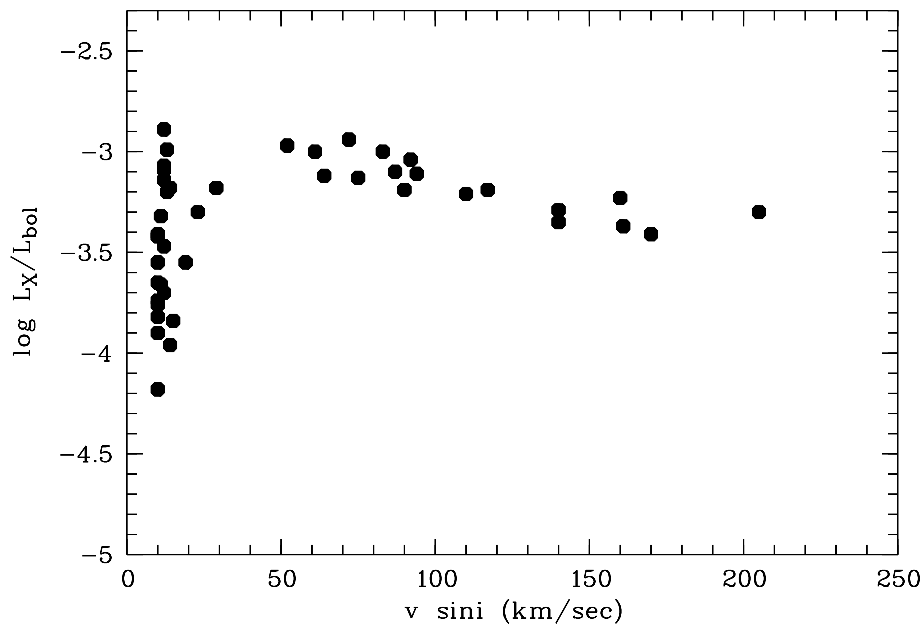

Figure 1. Ratio of X-ray to bolometric luminosity for α Persei stars. Stars with $0.6 <$ B–V$_0$ <1.45 are considered.

fast rotators which are observed in young clusters (e.g., Collier Cameron and Li 1994; Barnes and Sofia 1996; Krishnamurthi et al. 1997; Bouvier et al. 1997).

The threshold velocity above which saturation is seen is different for the various activity diagnostics and depends on stellar mass. If one studies the activity – rotation relation considering the Rossby number (the ratio of the rotational period to the convective turnover time, $N_{\rm R} = {\rm P}/\tau_{\rm c}$) instead of rotational velocity or period itself (e.g., Noyes et al 1984; Simon et al. 1985), a critical Rossby number $(N_{\rm R})_{\rm crit.}$ is determined below which the relation saturates (e.g., Patten and Simon 1996; Stauffer et al. 1997a). Since $\tau_{\rm c}$ is a function of stellar mass (namely, it increases with decreasing mass), saturation will start to be seen at progressively larger periods for stars of lower masses. Stauffer et al. (1997a), using Noyes et al.'s analytical approximation for $\tau_{\rm c}$, estimated that saturation should occur at P = 2d (v(rot) $\sim$ 25 km/sec) for 1 $M_\odot$ stars and at P = 4.5d (v(rot) $\sim$ 5 km/sec) for 0.4 $M_\odot$ stars. In addition, Stauffer et al (1997b) recently suggested that different rotational histories, and specifically the presence or not of a circumstellar disk locking the star during pre-main sequence contraction, could lead to different dynamo-induced magnetic activity, and eventually to different saturation velocity thresholds.

So much, as far as the low velocity tail of the saturation relation is concerned. What about the high velocity end, then? Very young open clusters, like the 50 Myr old α Persei or the 30 Myr old IC 2602 and IC 2391, have a population of cool ultra fast rotators (UFRs), or G and K-type dwarfs with projected rotational velocities exceeding 100 km/sec. ROSAT observations of the IC clusters (Randich et al. 1995; Patten and Simon 1996) and of α Per (Randich

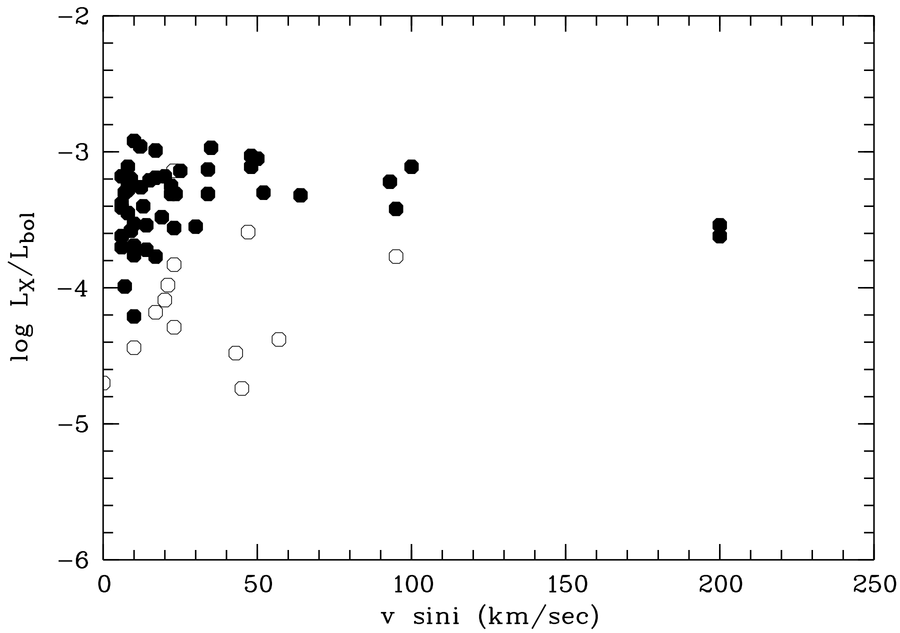

Figure 2. Same as figure 1, but IC 2391 and IC 2602 members are shown. Filled and open circles denote stars with $(V\text{-}I)_{C0} < 0.70$ and $0.4 < (V\text{-}I)_{C0} < 0.70$, respectively.

et al. 1996; Prosser et al. 1996) covered many of these UFRs, allowing to study what happens to the activity-rotation relation for stars with extreme rotational velocities.

2. What is "supersaturation"?

In Figure 1 $\log L_X/L_{bol}$ ($\log R_X$) is plotted vs. $v\sin i$ for α Persei; Figure 2 is the same, but IC 2602 and IC 2391 stars are shown, whereas Figure 3 (from Patten and Simon 1996), shows $\log R_X$ vs. the logarithm of the Rossby number ($\log N_R$) for stars in the field, and in the IC 2391, α Per, Pleiades, and Hyades clusters.

The three figures show similar patterns: above a critical velocity or below a critical Rossby number, the saturation plateau discussed in the Introduction is clearly seen (the scatter in the IC 2602/2391 plot for $v\sin i$ between 15 and 30 km/sec reflects the scatter in mass and the fact that stars with different masses have different saturation thresholds; see the discussion in Stauffer et al. 1997a). However, most surprisingly, UFRs (or, more generally, stars with very low Rossby numbers) do not lie at the saturated level $\log R_X = -3$, but show a decline from it. This phenomenon has been termed "**supersaturation**" by Prosser et al. (1996).

Supersaturation starts to be seen for $v\sin i \gtrsim 100$ km/sec, or for Rossby numbers $\log N_R$ between ~ -1.6 and ~ -1.8. The decline in $\log R_X$, which is as large as a factor of 3–5, is observed for a significant number of stars and in

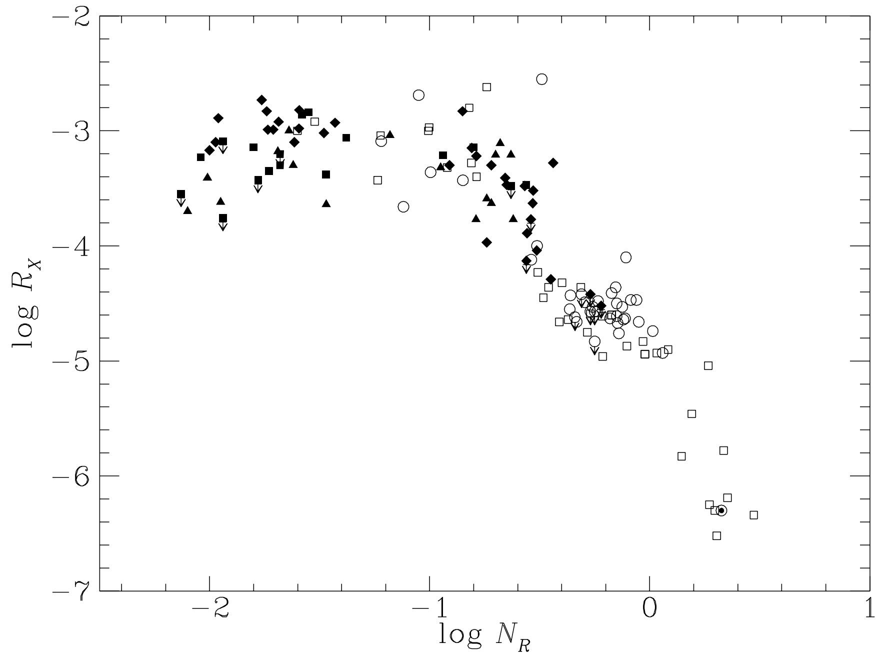

Figure 3. log L_X/L_{bol} (R_X) is plotted vs. log Rossby number ($\log N_R$) for: IC 2391 (filled triangles), α Per (filled squares), the Pleiades (filled diamonds), the Hyades (open circles), and main sequence field stars (open squares). The Sun is also plotted.

more than one cluster, thus I regard as unlikely that it is due to uncertainties or errors in the estimates of X-ray luminosities. Moreover, it is also improbable that supersaturation is 'produced' by some effect of rapid rotation on bolometric luminosity. Whereas very rapid rotation has been shown to modify stellar structure, resulting in a change of colors and luminosity (e.g., Kraft 1970; Maeder 1971), this effect is at most of the order of 20 %, much smaller than the observed decrease in $\log R_X$. I therefore conclude that supersaturation indicates a real decrease of X-ray emission –at least in the ROSAT passband.

3. Discussion

Before discussing the possible causes of supersaturation, I wish to address two questions; First, is supersaturation seen in other classes of stars (specifically, fast rotators) apart from the ones in young clusters? Second, is supersaturation observed for other magnetic activity indicators?

In Figure 4 $\log R_X$ vs. log P is plotted for α Per stars, the sample of BY Draconis and RS Canum Venaticorum active binaries from Dempsey et al.

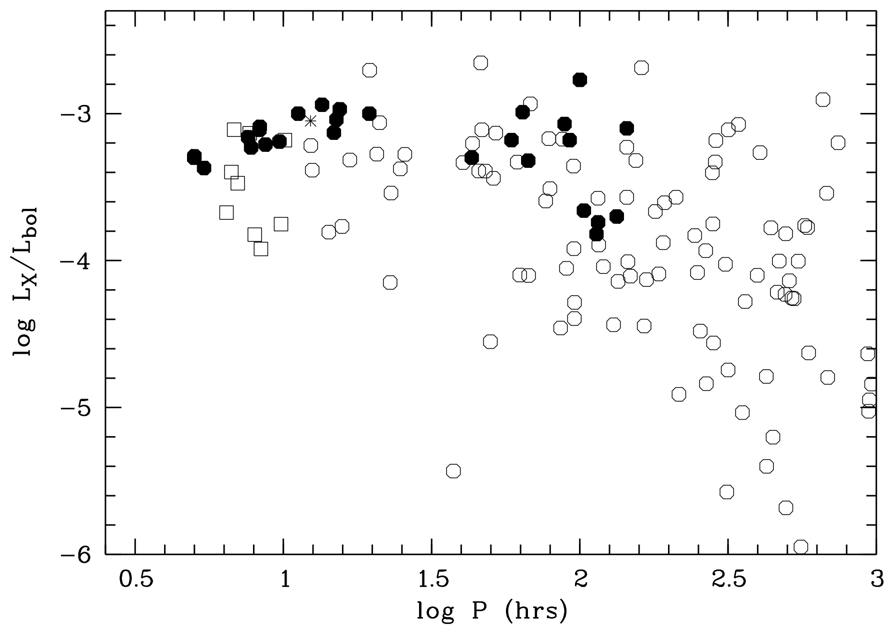

Figure 4. $\log \mathrm{R_X}$ vs. period for: α Per (filled circles), RS CVn and By Dra binaries (open circles), W UMa systems (open squares), and AB Dor (asterisk).

(1997) and Dempsey et al. (1993) [1], and for a small sample of W UMa contact binaries from McGale et al. (1997); the active star AB Dor is also plotted in the figure (asterisk; data from Kürster et al. 1997).

Fig. 4 first shows that, as noted by Dempsey et al., the distribution of active stars is characterized by a significant scatter; a few short-period but very low $\mathrm{R_X}$ systems are present and, at the same time, stars at the saturation level, or close to it, are seen already at longer periods than in α Per. AB Dor, with a period of 12.5 hrs, is at the saturation level. Most of the very-short periods binaries, which however have longer periods than α Per supersaturated stars, are indeed below the saturation level; however, since the saturation plateau for RS CVn and BY Dra binaries is not as sharp as for the young clusters, it is difficult to ascertain whether this is a real decline in $\mathrm{R_X}$ for the most rapidly spinning binaries. On the other hand, as suggested by S. Drake in his question at the Workshop, W UMa binaries seem to be 'supersaturated', showing a decline from saturation even larger than UFRs in α Per.

In Figure 5 $\log f_{\mathrm{H}\alpha}/f_{\mathrm{bol}}$ is plotted vs. $\mathrm{v}\sin i$ for α Per stars for which Hα data are available. Hα fluxes have been derived from published equivalent widths using the relationship given by Soderblom et al. (1993). Although the number of points in the figure is rather small, the saturation relation seems to

[1] Note that Dempsey et al. (1997) do not find any statistically significant differences between the coronal properties of RS CVn and BY Dra systems and, in particular, they state that the dependence of X-ray flux on period is the same for the two groups.

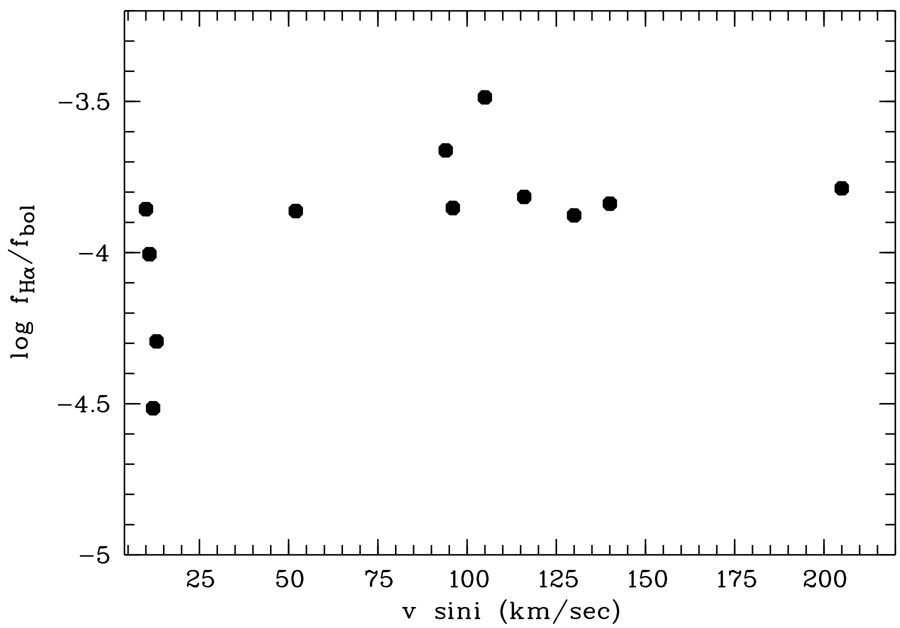

Figure 5. $\log f_{\mathrm{H}\alpha}/f_{\mathrm{bol}}$ vs. vsin i for α Per.

be well defined and there is no evidence for a decline from the saturated ratio at very high vsin i values, i.e., supersaturation is not seen for Hα.

I do not have an explanation at hand for supersaturation -probably we should fully understand saturation first! However, addressing the problem, and hopefully giving an answer to it, would help towards our general understanding of stellar dynamo. In the following, I shall discuss an observational test which should permit us a better comprehension of the physical reasons that lie behind the observed phenomenon of supersaturation. Namely, two hypothesis can be done. On the one hand, supersaturation could be the result of an overall decrease of dynamo efficiency at very high rotation. On the other hand, supersaturation in X-rays could just mean that more relatively cool plasma (with T $\sim 10^5$ K) is heated, emitting UV and EUV radiation, rather than coronal plasma. This, on turn, could be a consequence of the decrease of the apparent surface gravity due to enhanced rotation. A lower stellar surface gravity implies an increase of the gravitational scale height of coronal plasma; more loops at temperatures of the order of 100,000 K may then exist, since such cool loops with height lower than the gravitational scale height are stable (e.g., Antiochos and Noci 1986; Antiochos, Haisch, and Stern 1986). If this is the case, one would expect an increase of radiative losses at this temperature, i.e. the emission line flux from the C IV doublet at $\sim$ 1550 Å should increase. To conclude, C IV fluxes for supersaturated stars, and in particular the comparison with X-ray data, would give a key to discern whether supersaturation is indicating supersaturation of the dynamo or, more simply, the readjustment of the radiative output from the corona to lower temperature.

An alternative, completely different explanation which was suggested by M. Gagnè during the discussion at the Workshop (see the question below), is that, with increasing rotation, coronal temperature also increases (see also A. Collier Cameron's comment) and most of X-ray emission moves out of the ROSAT passband. With future X-ray missions it will indeed be possible to obtain X-ray spectra extending to higher energies than ROSAT [2]. This will allow us to ascertain whether there is a shift of the coronal emission measure distribution (DEM) outside the ROSAT passband. It is important to note, however, that McGale et al. (1996) find that W UMa binaries appear to have, in general, relatively less emitting material at high temperatures than RS CVn and BY Dra systems.

4. Summary

- ROSAT data for young clusters have shown a decline of the L_X/L_{bol} ratio from the saturated value for the so called UFRs. The decrease starts to be seen at $v\sin i \gtrsim 100$ km/sec, or $P \gtrsim 8$ hrs, or $\log N_R \lesssim -1.8$;
- supersaturation -that is how this phenomenon has been named- is most likely a real effect;
- it is not clear whether active RS CVn and BY Dra systems exhibit supersaturation as well; W UMa contact binaries, instead, show supersaturation;
- supersaturation is not seen for Hα emission, at least as far as α Per is concerned;
- whereas supersaturation cannot be easily explained with the current understanding of stellar dynamo, a straightforward test would allow to check whether it is the consequence of a decrease of the efficiency of stellar dynamo or, less dramatically, of the redistribution of the heating to the cooler, transition region plasma;
- alternatively, very rapid rotation could lead to a substantially higher coronal temperature and to the shift of the DEM out of the ROSAT passband.

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Discussion

Marc Gagné: (Comment, 1st): The field M dwarfs and the BY Dra variables show supersaturation as well, with saturation kicking in at $6-10$ km/sec and supersaturation above $40-100$ km/sec.

[2] ASCA and SAX would not provide a high enough sensitivity for supersaturated UFRs in the α Per or IC2602/2391 clusters.

(Comment, 2nd): Another interpretation of the ROSAT results is that UFRs have hotter coronae and that their emission has moved out of the ROSAT pass-band.

: Yes, I agree on your 2nd comment. Thanks for stressing this. As to your first comment, it seems to me that it is not actually clear from the figure I have shown whether BY Dra binaries are supersaturated or not.

Steve Drake: Were contact binaries included in the plot that you showed of binary stars' X-ray emission vs. period? I ask because a number of years ago there were claims that contact binaries transition region and coronal emission did lie below what was expected from an extrapolation of (non-contact) RS CVn binaries; this may then be consistent with the claim of 'supersaturation' seen in rapidly rotating cluster stars.

: Contact binaries were not originally included in the plot, but added in afterwards (see Sect. 2) and they indeed appear to be supersaturated.

Andrew Collier Cameron: A couple of comments. First, Vilhu showed that C IV saturates at relatively low rotation rates, so there is no clear evidence for an increase in the 10^5 K emission measure from "supersaturated" stars. Rather, the coronal temperature increases with increasing rotation rate.

Second, the supersaturation phenomenon appears to set in at rotation rates such that the co-rotation radius lies within one stellar radius or so of the surface. The centrifugal forces on the loop plasma should lead to shrinkage of the coronal volume.

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